NEW RESIDUAL STRESS MAPPING TOOL APPLIED TO ATLAS CURRENT JOINT DESIGN

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Abstract

A redesigned cylindrical liner system has been implemented for use on the Atlas capacitor bank. This new design dramatically changes how the liner, glide planes and current joints of the system are formed. The previous design relied on interference of the liner with the glide plane by thermal shrink fit using liquid nitrogen coolant to form current joints. The new design achieves the required fit by mechanically distorting soft metals with a swaged joint. In this paper, we present the results of the first application of a new residual stress mapping technique, the contour method, to the design and fabrication process of the Atlas upper current joint. One of the strengths of the contour method is that it provides a full cross-sectional map of the residual-stress component normal to the cross section. The results showed significant stresses in the stainless steel glide plane with expected maximum compression near the joint and stresses in the aluminum part liner and return current conductor that corresponds well with measured form distortions.

I. INTRODUCTION

The redesigned joint swages an ultra-pure, extremely soft aluminum liner between a stainless steel glide plane and a relatively strong aluminum counter bore in the return current conductor. This joined the glide plane, liner and return conductor into an inseparable assembly [1].

The upper joint is of particular concern because of its proximity to the active portion of the liner; the portion between the two glide planes that accelerates radially inward by jxB forces during the current pulse. The electrical integrity of this joint is critical to proper initiation of the magnetically driven, convergent geometry, implosion of the liner. Local liner distortions are inevitably caused by interference joining of materials, but these distortions must not propagate into the active portion of the liner since the liner has a requirement to be straight, with uniform wall thickness in this region.

The current joints are presently being redesigned because they are not strong enough. The joint was made by a thermal shrink fit technique that relied only on the strength of a thin, 1100, aluminum liner. This posed a risk that the liner may separate from the glide plane either during assembly or during the shot. As with any redesign of this importance to the system, this new joint design needed to be tested and optimized. A prototype test part was fabricated that represented the critical joint elements. Then form measurements on the liner and return current conductor were made to determine to what degree the liner form is impacted by the new upper joint.

The measurements showed excessive liner form distortions adjacent to the joint that extended into the active liner region. It was decided that a measure of the residual stresses in the joint region might provide insight into how the joint was behaving and prove useful for the joint optimization process.

Recently, a new method for measuring residual stress, the contour method, has been introduced [2,3]. This technique was developed at Los Alamos and one in which the authors, M. Prime and R. Sebring, have been working on the non-contact laser surface profiling aspects for the past three years [4,5,6,7]. In the contour method, a part is carefully cut in two along a flat plane causing the residual stresses normal to the cut plane to relax. The contour of each of the opposing surfaces created by the cut is then measured. The deviation of the surface contours from planarity is assumed to be caused by elastic relaxation of the residual stresses and is therefore used to calculate the original residual stresses.

A two axes laser scanner that was custom built in our lab was used to capture the line and topographic contours. Non-contact scanning is not a requirement for the contour method; a coordinate measuring machine with a contact probe may be used as well [8,9]. The non-contact method is preferable because it is more precise and accurate, faster, provides greater spatial point density and does not damage the part surface. The significant application of laser scanning to residual stress measurement is new but contouring by scanning with a laser probe is a proven technology that can provide a more accurate surface contour than can a touch probe [10].

One of the unique strengths of the contour method is that it provides a full cross-sectional (2-D) map of the residual stress component normal to the cross section. Other relaxation methods, at least those that are commonly used, determine at most a 1-D depth profile [11].

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14. ABSTRACT
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II. UPPER CURRENT JOINT DESIGN

The upper joint is being redesigned to eliminate a problematic thermal shrink fit joint and replace it with a stronger swaged compression joint. The joint is now formed by compressing a pure aluminum liner between a 303 stainless steel glide plane and the 6061-T aluminum return current conductor. In order to perform dimensional and residual stress measurements, a prototype test part of the upper portion of the liner assembly that included the upper joint was fabricated. The swage fit was accomplished by sliding a 303 stainless steel glide plane inside the liner open end and pulling it down past the interference region with a series of bolts through the return current conductor (Fig. 1). The test part differed from the full liner which is longer, gets larger and thicker at the lower glide plane and is closed at the end by the lower conductor plate (Fig.2). The prototype design had a maximum interference fit of 0.009" over a length of 0.175" inches between the glide plane and the liner and a .0012" gap between the liner and the return conductor counter bore (Fig. 3).

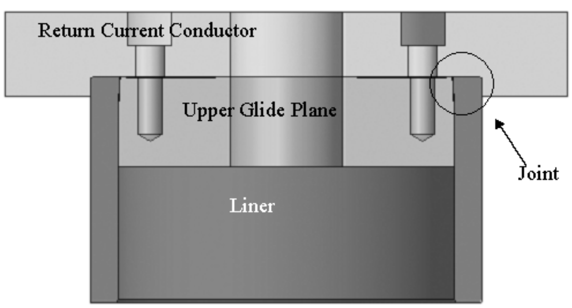

Figure 1. Drawing of upper joint prototype test part.

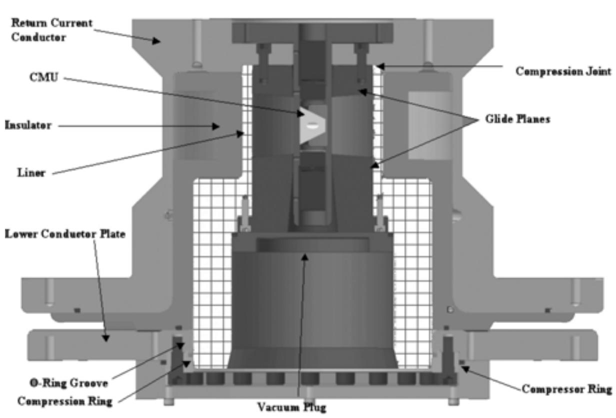

Figure 2. Cassette assembly. Note relationship of upper current joint (labeled compression joint), liner (hatched region) and glide planes.

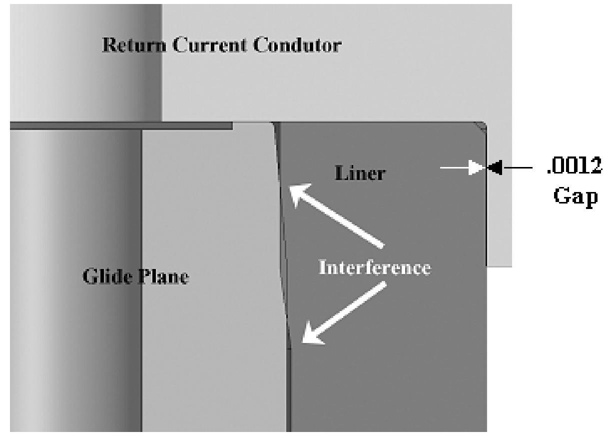

Figure 3. Detail of joint (circled region in Fig. 1.)

III. CONTOUR METHOD

A. Part Cutting

The first step in measuring residual stresses with the contour method is to cut the part in two (Fig. 4). Currently, the ideal method for making the cut has proven to be wire electric discharge machining (EDM), a widely used manufacturing process. Wire EDM is ideal because it makes a very straight cut, does not remove additional material from previously cut surfaces, does not induce plastic deformation, and results in negligible induced stresses if cutting is performed under the proper conditions [12]. The test part was cut with a Mitsubishi SX-10 wire EDM machine and 150µm diameter brass wire. The part must be constrained from moving as stresses are relaxed during the cutting. For the test part, such constraint was achieved by clamping the part at eight places around the return conductor whereas usually for wire EDM only one side of the work piece is clamped.

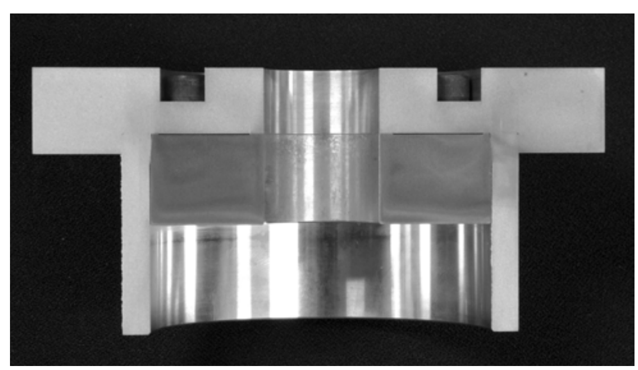

Figure 4. Photograph of upper joint prototype test part cut in half with wire EDM.

B. Laser Contouring of Cut Surface

After cutting in half and unclamping the test part, laser surface contouring was performed using a custom built, non-contact measuring machine. The scanning system was operated from a PC through a graphical user interface running LabView® software. The motion hardware used for this task consisted of two, orthogonal, linear axes with precision air-bearing box slides, non-contact linear motors with a resolution of 0.05 μm and 8 inches of travel. The X and Y motion axes were stacked. The part was fixtured near the center of travel with the cut surface facing upwards. A confocal laser ranging probe (Model LT-8105, Keyence Corp.) was fixtured to the optics table next to the motion stack. The probe was suspended from a horizontal bar such that the laser pointed downward, normal to the cut surface (Fig.5).

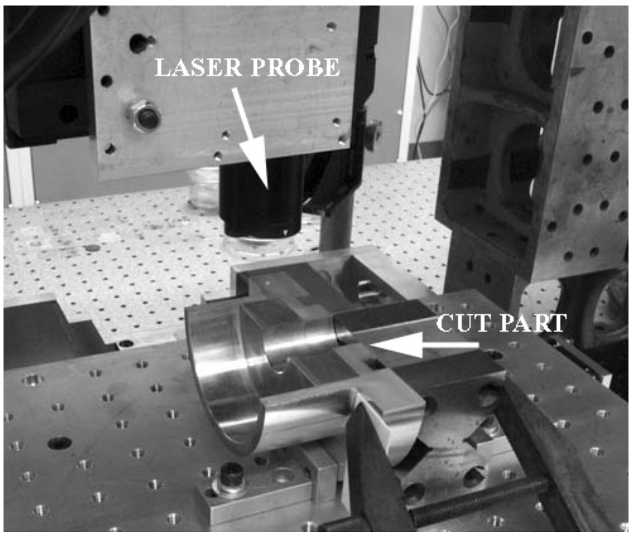

Figure 5. Non-contact laser scanning setup.

The probe has a 7μm diameter spot size, a measuring precision of ±0.2 μm and performs distance measurements at 1.4 GHz. Probe calibration was performed using a NIST traceable optical step height gauge. The part was moved in X and Y directions while the laser remained stationary. Once setup, the scanner runs automatically. Approximate scan duration was 1.5 hrs, resulting in a point cloud with 0.1 mm point spacing on the entire surface.

C. Stress Calculations

The stresses that were originally present on the plane of the cut were calculated numerically by elastically deforming the cut surface into the opposite shape of the contour that was measured on the same surface. This was accomplished using a 3-D elastic finite element (FE) model. A model was constructed of one half of the part—the condition after it had been cut in two—but with the cut surface modeled as flat instead of the slightly deformed shape measured by the surface contours. The material behavior for aluminum was modeled as isotropic linearly elastic with Young's modulus of 70 GPa and Poisson's ratio of 0.33, and the stainless steel used 195 GPa and 0.3 respectively. For the stress calculation, the opposite of the measured surface contour was applied as displacement boundary conditions on the surface corresponding to the cut. The unique specimen measured here required more sophisticated calculations than those done previously with the contour method. A detailed discussion is beyond the scope of this paper, but the general idea can be outlined. Because the various pieces were not bonded but rather just secured by an interference fit, they were free to move relative to one another. Therefore, in the FE model the aluminum-steel interface was modeled as a frictionless contact surface. In the preliminary calculation reported here, friction was neglected, as were contact between the two aluminum pieces and the affect of the bolts.

Several steps were used to process the discrete surface contour data (point cloud) into a form suitable for calculating the stresses with the FE model. The point clouds from the two opposing surfaces created by a cut were aligned to each other. Then each cloud was fit to a bivariate Fourier series. The fits to the two opposing surfaces created by the cut were then averaged; averaging the two contours is crucial to minimize several error sources. Finally, heights of the smoothed surface were evaluated at the coordinates of the nodes in the finite element model, the signs were reversed, and the results were written into the FE input deck as displacement boundary conditions. This process was repeated four times: once each for the aluminum and steel on one side of the symmetry axis and then again on the other side.

IV. RESULTS

Figure 6 shows the form results of the liner for the new swage joint and old shrink fit joint. It distorted the liner to a greater degree than the older style shrink fit joint. With the new joint there is a prominent rise, corresponding to an increase in liner outside diameter, adjacent to the joint and a gradual fall off into the active liner region. The magnitude of this bulge is consistent with the .009" (230 um) interference of this joint, however it impacted the entire test liner length. This includes the active region of the liner, which is highly undesirable. The equivalent region on the shrink fit joint showed far less distortion overall with an acceptable straightness in the active region. This is consistent with the smaller amount of interference of this particular design but the small interference was also responsible for the weakness of this joint. The reason there is no data in the first 10 mm of the shrink fit liner is that it had a machined feature designed to augment magnetically induced pressure at the current joint during early current rise, so its form was not comparable to the other liner in that region.

Figure 7 shows the contour method results. The figure shows the circumferential (hoop) stresses over the cross section of the assembly. The most significant stresses are the compressive stresses towards the outer diameter of the steel glide plane, which are consistent with the swage fit. The stress magnitudes, below 150 MPa for most of the stress map, is quite reasonable considering that a typical yield strength for 303 stainless steel is over 200 MPa in the annealed state and higher after cold work. Towards the inner diameter of the glide plane, the stresses are more tensile than expected, which may be caused by bending moments that exist between the bolts, or may be caused by pre-existing residual stresses from the making of the ring. The stresses are lower in the aluminum parts. The highest stresses in the aluminum might be expected to be the stresses from contact with the glide plane. Those stresses would be radial or axial stresses, and are not revealed by this measurement. Furthermore, because soft aluminum was used for the liner, it was not expected to support much stress.

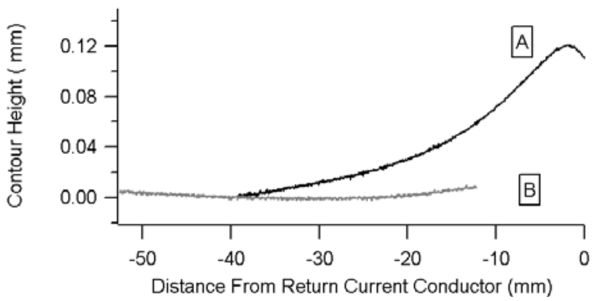

Figure 6. Graph of liner forms. The current joint is at the right side of graph. Line '**A**' is the form of the new style, swage fit joint system and '**B**' is the form of older style, shrink fit joint system.

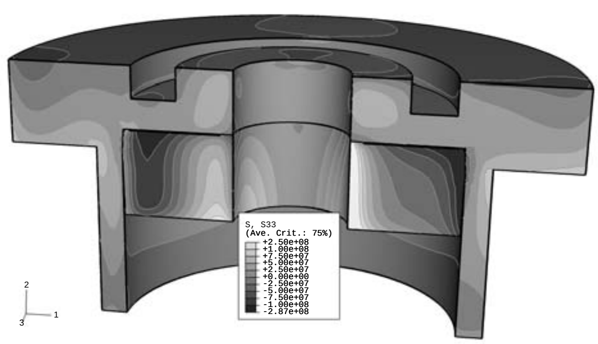

Figure 7. Measured hoop stresses on cross-section of upper joint test part. Stresses are given in Pa in intervals of 50MPa, and darker regions are compressive.

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